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Abstract

Generally, researchers consider sustainability and resiliency aspects of infrastructure projects independently, without considering the relationship that exists between them. Unified approaches that combine sustainability, resiliency, and analyze risk are very minimal. This paper proposes a unified approach to assessing sustainability, resiliency, and risk for infrastructure via evaluating the performance of a tailings dam under various earthquake magnitudes. A tailings dam is typically in operation for many years, which means they may have a direct impact on the local environment, society, and economy. Due to the extended life of the dam, the probability of a major event occurring that could negatively impact the durability of the dam increases. Hence, it is important to study impacts on the environment and economy under regular (sustainability analysis) and extreme (resiliency analysis) conditions in conjunction with their probabilities of occurrence. This paper studies the interrelationships between sustainability, resiliency and the potential risks of a negative impact upon infrastructure. Results provided show that a unified approach with emphasis on risk offers a more holistic, and accurate depiction of a system's overall quality.

Keywords: sustainability, resiliency, risk, unified approach, Tailings Dam

Introduction

In consideration of the potential hazard to the world's ecology, researchers and engineers have begun discussing methods to asses and design civil infrastructure with considerations of sustainability and resiliency. Sustainability is defined by the American Society of Civil Engineers, as "a set of environmental, economic, and social conditions - the "Triple Bottom Line"- in which all of the system has the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality or the availability of natural, economic, and social resources" (American Society of Civil Engineers 2017). Resiliency is commonly identified as a system that undergoes a loss in functionality due to an event that has low probability but high impact, and that system regaining functionality within a specified time. For a system or project to be considered resilient, it must meet criteria outlined by four pillars of resiliency; robustness, resourcefulness, rapidity, and redundancy (Bruneau and Reinhorn 2006). Further, definition of resiliency includes a probabilistic assessment of the system. The probability of an event that could impact the functionality of a system, and the probability of impact on functionality due to that significant event, is resiliency as outlined by Chang and Shinozuka (2004).

Numerous researchers (Basu et al. 2015; Haeri 2016; Lee 2016) have outlined procedures to perform sustainability and resiliency assessments separately in a mutually exclusive fashion, while few have measured the effectiveness of unifying these assessments. Bocchini et al. (2014) identified the inefficiencies in considering sustainability and resiliency impacts separately mainly because of the vast number of similarities and common characteristics between the two. For example, both analyses require life cycle assessments to study the impacts and both analyses study the impact of the infrastructure through impacts on economy, environment and society. Hence, Bocchini et al. (2014) outlined a unified approach to sustainability and resiliency assessments for various civil infrastructure. Researchers also made special note that risk theory should be incorporated into the assessments in order to have systematic unification of resiliency and sustainability. This is largely due to the close relationship risk has with the concept of resiliency, and the interconnectedness of sustainability and resiliency. Also, if risk is neglected there is an increased potential for designing infrastructure that may be inadequate or susceptible to failure. Accounting for risk allows decision makers to properly identify design alternatives that may best suit their needs, while ensuring the design meets sustainable and resilient parameters. Proposed here is a unified approach that uses the concepts of probability of occurrence and risk in order to address resilience and sustainability of the civil infrastructure simultaneously and quantitatively. The potential benefits of a unified approach for sustainability, resiliency, and risk are outlined using a model of a theoretical tailings dam. The analysis performed for this paper is divided into two sections; individual sustainability and resiliency assessments, and unified sustainability, resiliency, and risk assessments. An example of a proposed tailings dam is provided to show the added benefit of including risk into the unified approach by comparing the results from the discrete and unified approaches.

Lèbre and Corder (2015) mentioned that sustainability and resilient concepts are interlinked for mining operations, as a mine cannot be sustainable if it is not resilient enough to stay in operation for the entire life cycle of the mine. In the event of closure, waste material is either left without proper rehabilitation or mitigation, which may reduce the functionality of the tailings dam, and decrease the sustainability (Lèbre and Corder 2015). Considerations for risk concepts are outlined in the work on risk analysis performed by Baecher and Christian (2000), as they identified the total amount of dams in the United States are over 75,000 and the average dam failure rate is approximately 7.5 dams per year. This shows that dams currently hold a high risk for failure, and efforts to mitigate these failures are needed within the mining industry.

Tailings Dam Analyses

A potential mine located in southwest Idaho will be mining molybdenum and copper deposits, and will require a tailings dam to store waste material from the mine. Due to the quantity of valuable material, this project has the potential to have significant environmental, social, and economic impacts in the Boise area. By industry standards, tailings dams are typically constructed to be impervious, earthen dams, which grow in height as the mine grows in depth (Davies et al. 2002). Prior to any material or slurry being contained by the tailings dam, a starter dam must be constructed (Hamade 2013). Starter dam is a critical aspect of a tailings dam and the stability of this dam is crucial to the overall stability of the tailings dam. Earlier analyses performed by Robbins and Chittoori (2017) showed that this starter dam should have a slope of 2.5 horizontal to 1 vertical and a height of 15 m while the overall height of the tailings dam was needed to be 250 m to ensure the reservoir was large enough to contain all the projected waste material produced from the mine.

From the work performed by Robbins and Chittoori (2017), the tailings dam was shown to be safe against an earthquake of magnitude 5.5, although it could be argued that the dam needs to be safe against higher magnitude earthquakes. This would alter the geometry of the starter dam and as a result alter the geometry of overall tailings dam. This change would have impacts on the sustainability of the entire mining operation. Hence, it is important to study the dam under various magnitude earthquakes along with the likelihood of their occurrence. In order to study this in detail, the starter dam was subjected to five different magnitudes of earthquakes ranging from 5 to 7 and the probability of failure under each of these magnitudes was recorded. Further, the slope of the starter dam was altered from 2:1 to 3.5:1 to study which of these slopes would be safe under the different magnitude earthquakes. After this information was established, separate sustainability and resiliency assessments in the form of cost to construct and cost to recover were analyzed for each case. Finally, a unified approach to sustainability and resiliency assessments including risk theory was used to study each of the slopes and earthquake magnitudes. The following sections detail each of these analyses along with the results and discussion.

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Numerical Model of the Starter Dam

Figure 1 shows the numerical model of the starter dam with a slope of 2.5 horizontal to 1 vertical and a height of 15 m. The internal geometry of the starter dam consists of a porous layer, located vertically along the centerline of the dam and horizontally across the downstream slope at the base of the dam to direct fluid flow and lower the phreatic surface. A geotextile was utilized next to the porous layer to prevent internal erosion, piping, or liquefaction caused by fluid flows exceeding maximum allowable velocities. It was assumed that the starter dam will be constructed using the waste from mining operations. Since these materials were not tested, the material properties were obtained from literature for waste material produced by similar mine. Values obtained from the literature (Bhanbhro 2014; Holmqvist and Gunnteg 2014; Hu et al. 2016) were used as the upper and lower limits for computational analysis. It was assumed that the properties were normally distributed between these upper and lower limits. The purpose of using researched data was to design the dam using materials that have been tested and their mechanical properties verified, which ensures that the results are 'realistic'. Assigning a distribution to the given values allowed for a statistical variance to be modeled within the software given variation in actual material properties. Various types of distributions are available for analysis, however for simplification a normal distribution was used for this analysis. Values obtained from research such as void ratio, unit weight, friction angle and hydraulic conductivity are shown in Table 1.

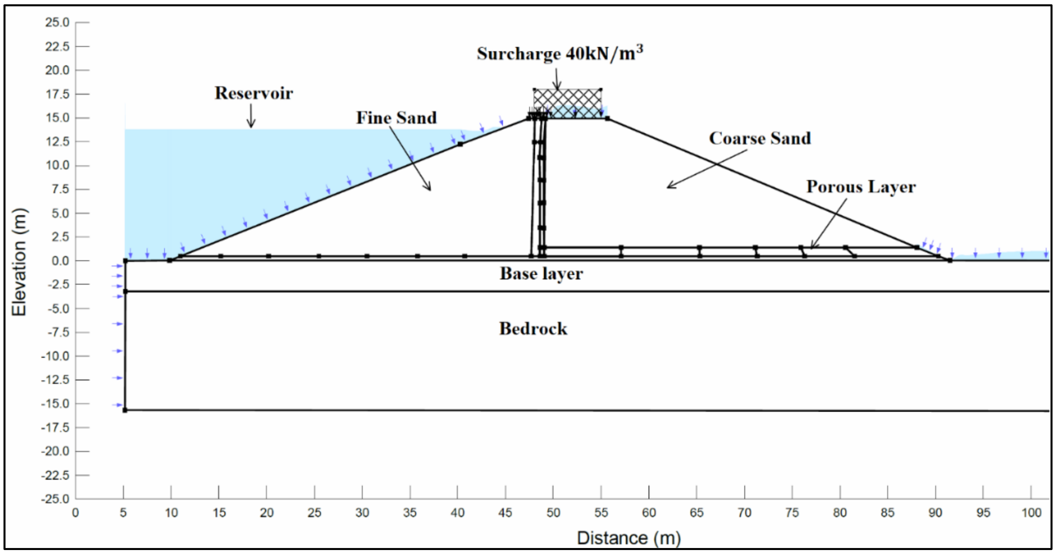

Figure 1: Tailings dam model layout, and dimensions.

Table 1 Geotechnical properties of soil used for construction of tailings dam

Soil	**Unit Weight (kN/m^3)**	**Hydraulic conductivity m/s**	**φ'**	**Poisson's Ratio**	**Damping Ratio**	**e**
Course Sand	23.5	1.1E-01	42	0.45	0.1	0.84
Fine Sand	17.7	5.7E-05	32	0.33	0.3	0.99

Evaluation of the starter dam stability was performed by analyzing seepage, slope stability, and earthquake resilience by use of numerical software GeoStudio (GEO-SLOPE International Ltd 2016). Seepage was analyzed to ensure internal erosion, or liquefaction does not occur within the dam due to seepage velocity exceeding the maximum. An assumption was made that the viscosity of the liquid flowing through the dam was equal to water to model the worst-case scenario. Maximum allowable seepage velocity was assumed to be 4 cm/s, as suggested by Richards (2012).

Slope stability was analyzed using Bishop's method of slices. Material properties for the soil were assumed from published data by Bhanbhro (2014), Hamade (2013), and Wang et al. (2015). Variation in material properties were accounted for by use of Monte Carlo simulations. Material density values were normally distributed between known maximum and minimums, and assigned a standard deviation of 0.5 to account for variation in the engineered particles.

Monte Carlo simulations varied the material properties to determine which were the most probable, and those most probable were then used to determine a Factor of Safety (FoS). For each simulation, slope stability calculations were performed by Bishop's method of slices, and finite element analysis within the previously mentioned software. From this analysis, a Probability Density Function (PDF) was produced, and the mean value provided within the PDF was used as the most probable FoS.

Sustainability Assessments

In this study, sustainability assessments were conducted considering only economic and environmental aspects. The economic aspects include the economic viability i.e. cost benefit comparisons whereas environmental aspects include the calculation of Embodied Energy (EE), and Embodied Carbon (EC). Measuring EE and EC shows how much energy was consumed and how much carbon was produced in constructing the project, which can be directly correlated to environmental impact. An additional method used for assessing the sustainability of the dam was a modified Life-Cycle Cost Analysis (LCCA). For the purpose of this analysis, the LCCA was computed by analyzing cost directly associated with the construction and rehabilitation of the tailings dam. A generalized assumption was made that any costs associated with the operation of the mine were essentially similar for all scenarios, and able to be neglected for this analysis.

Discrete sustainability was measured by considering the economic and environmental impacts. Economic impact was based on a cost of construction for the tailings dam (Mosquito et al. 2015). An assumption was made that regardless of any action taken on the tailings dam, all social impacts would all be relatively similar between the different slopes of the starter dam. Social aspects were neglected during this analysis, however for the proposed framework social analysis should be considered and done by methods similar to guidelines outlined in the work by Valdes-vasquez et al. (2013). For environmental impact, tailing dam's model - using minimum dimension/slope requirement as per state law, was analyzed for safety against seepage and slope stability using the software without considering seismic activity. A series of static simulations were executed to establish the smallest dimensions possible that would satisfy minimum requirements. The computations on embodied energy, and embodied carbon for that dimension were computed using the Institution of Civil Engineers (ICE) database (Circular Ecology 2016).

Results from the sustainability computations show that the most cost effective construction method was to build the tailings dam with a 2:1 slope. This is due to the 2:1 sloped dam having to use fewer materials in construction which directly relates to environmental, and economic costs, as shown in Table 2.

Table 2 Results from Sustainability analysis

Slope (H:V)	EE (MJ)	EC ($kgCO_2$)	Cost (millions)
2:1	3.60E+10	2.08E+09	$305
2.5:1	4.48E+10	2.59E+09	$380
3:1	5.36E+10	3.10E+09	$454
3.5:1	6.23E+10	3.61E+09	$529

Resiliency Assessments

The definition of resiliency in this work is determined on the robustness of the tailings dam. Robustness of the tailings dam is based on functionality, which is representative of slope stability. For quantifying robustness, the tailings dam analyzed for its seismic performance in terms of the computed FoS. Slope stability was evaluated for both static analysis and seismic analysis. Probability of occurrence was used as a component within the seismic analysis. Given the location of the proposed tailings dam, the probability of being impacted by an earthquake ranges from approximately 50% for a magnitude 5, to 0.16% for a magnitude 7, as shown in Table 3. The PHA was used by the software to simulate the earthquake of varying magnitude. Linking PHA to magnitude of earthquake was determined by comparing PHA to the Modified Mercalli scale, then comparing the Modified Mercalli scale to the Richter scale (Robinson 2013; USGS 2017), as shown in Table 4.

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Table 3 Earthquake probabilities for Boise county Idaho

Earthquake Probability for Boise County Idaho						
Magnitude	0	5	5.5	6	6.5	7
Probability	1	0.5256	0.2631	0.1218	0.0468	0.0016

Table 4 Correlation between PHA, Modified Mercalli scale, and Richter scale

Richter Scale	1 to 2	2 to 4	4	4 to 5	5 to 6	6	6 to 7
Modified Mercalli Scale	I	II–III	IV	V	VI	VII	VIII
Acceleration (g)	< 0.0017	0.0017 – 0.014	0.014 – 0.039	0.039 – 0.092	0.092 – 0.18	0.18 – 0.34	0.34 – 0.65

Several analyses for seepage, slope stability and seismic stability were done using software and FoS for each PHA. Any FoS greater than or equal to 2.0 is considered 100% functionality, and any FoS less than or equal to 1.0 represents a catastrophic failure, or 0% functionality. A correlation between PHA, tailings dam dimension and FoS was then established. This methodology allowed for the evaluation of FoS based on probabilistic analysis, such that a computed FoS was then determined as a probability of failure, given the occurrence of an earthquake.

Results from the resiliency assessments show that to maintain functionality in the event of an earthquake, the tailings dam should be constructed with a wide base. For earthquakes that are magnitude 5 or less, the slope of the tailings dam may be as steep as 2:1. Magnitude 6 earthquakes require slopes of 3:1, while magnitude 7 may require a tailings dam slope of 3.5:1, as shown in Figure 2.

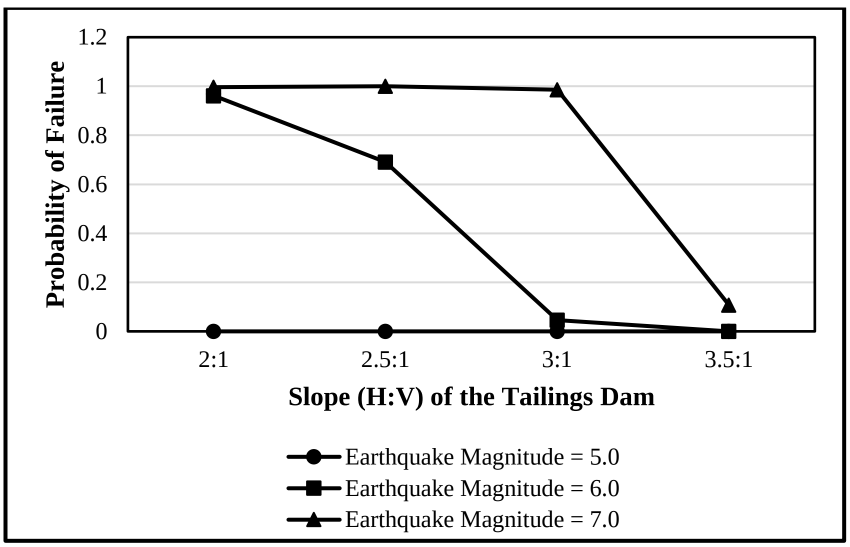

Figure 2: Graph of probability of failure vs tailings dam slope.

Unified Approach to Sustainability, Resiliency, and Risk

When evaluating for sustainability, the example shows that the most sustainable option for the tailings dam was to construct the dam with a slope of 2:1, which is the minimum required slope allowable for the state of Idaho. The sustainability analysis neglected the potential for an earthquake, and how the earthquake could impact the functionality of the tailings dam. Evaluation of resiliency for the example provided guidance for decision makers to construct a tailings dam that could sustain function from a low probable, but high impact event. This method shows a tailings dam constructed with the maximum width of a base analyzed proved to be more resilient than any other. However, the discrete resiliency analysis neglected the economic and environmental impacts that would occur from constructing a highly resilient, robust dam.

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To mitigate the issue of neglecting key aspects to developing civil infrastructure when performing a discrete analysis for either sustainability or resiliency, this paper proposes unifying the two assessment methods. In addition to assessing sustainability and resiliency, the use of risk as another aspect of the system's analysis to aid in quantifying the overall quality of the system, as shown in Figure 3. The unified approach to measure sustainability and resiliency is modified form of frameworks from Das et al. (2016), Bocchini et al. (2014) and Chang and Shinozuka (2004).

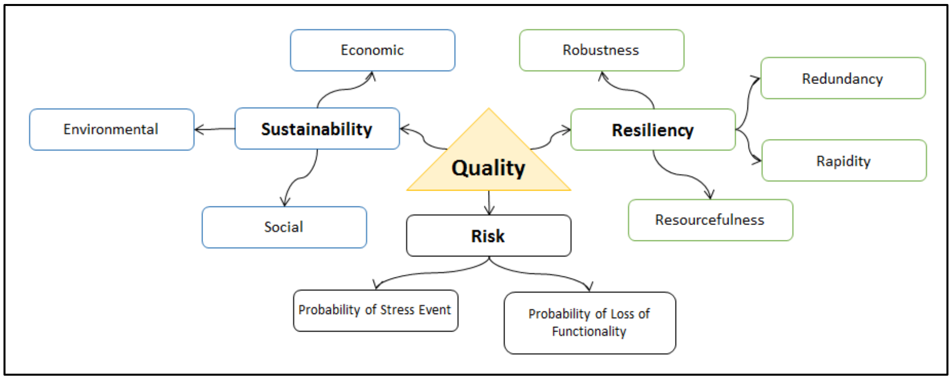

Figure 3: Flow chart for aspects that make up the total quality of a system

Procedural steps to implement the unified approach to assessing sustainability and resiliency with risk are intentionally short, concise, and relatively simple to perform. This simplicity allows for easy implementation within any aspect of civil infrastructure design. Step by step procedures are as follows:

1) When considering a design alternative, perform a cost analysis for all possible designs. The cost analysis could be for an entire life cycle, or just the initial costs.
2) Verify how the performance may be effected under various possible extreme events. Here use the probability of occurrence of each event, as well as measure the potential impact that event may have on the function of the infrastructure.
3) Use Bayes' Theorem to determine which extreme events are most likely to cause failure.
4) Estimate the cost of repair needed due to the occurrence of the extreme event, and express the cost as a function of probability of failure.
5) Combine costs from the first step with the repair costs along with their probabilities of occurrence and compare alternatives.

This proposed framework may be used to assist decision makers in determining the most effective design methods to support sustainability and resiliency.

Discussion

For the example provided in this paper, the tailings dam results for both the discrete sustainability and resiliency analysis suggested two opposing design methods. For the sustainability analysis, the tailings dam is recommended to be constructed by using the minimum state standards for slopes of 2:1. For the resiliency analysis, the results suggested constructing the tailings dam to have a wide, flat slope of 3.5:1 to sustain from high impact earthquakes.

Unifying the analysis for sustainability and resiliency coupled with risk allowed for examination of which design alternative had the highest probability of failure given the occurrence of an earthquake. This was then monetarized to allow for sustainable assessment of the tailings dam. Costs were normalized to the minimum cost of construction for the tailings dam. From the seismic analysis, the probability of failure was computed, and then used with the probability of occurrences for a given magnitude of earthquake. These results were then used in the Bayesian analysis to determine the probability that a certain magnitude of earthquake caused failure, given that a failure occurred. Each computed FoS was determined based on the variation in material properties provided by Monte Carlo simulations. The simulations were performed by varying the density and shear strength properties within the software, and the results obtained were plotted as a probability of failure vs. FoS graph. Using the mean value of the probability of failure, a

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respective FoS was then determined. This allowed to establish a relationship between the magnitude of earthquake and slope failure. Bayesian analysis was performed by collecting the known probabilities of earthquakes in the area where the dam is located. Then computing the probability of failure given the occurrence of each magnitude of earthquake, and each slope design of the dam. From this, the probability of failure given that a certain magnitude of earthquake occurs was computed.

From the results, the most probable failures were determined to be magnitude 6 earthquakes, on a 2:1 and 2.5:1 slope ratio, a magnitude 6.5 on a 3:1 slope, and a magnitude 7 for a 3.5:1 slope, as shown in Table 5.

Table 5 Results of probability of failure by use of Bayes' Theorem

Bayes' Theorem				
PoF	**Magnitude**			
slope (H:V)	**5**	**6**	**6.5**	**7**
2:1	0.00	0.71	0.28	0.01
2.5:1	0.00	0.63	0.35	0.01
3:1	0.00	0.11	0.87	0.03
3.5:1	0.00	0.00	0.00	1.00

Cost of repair was assumed to be the percent of functionality lost, multiplied to the construction cost. Cost of repair added to the initial costs without the consideration for risk showed that the lowest average cost total was the tailing dam with a 3.5:1 slope, as shown in Figure 4. When incorporating risk into the unified approach, the total cost was shown to be the lowest for the tailings dam with a 2:1 slope, as shown in Figure 5.

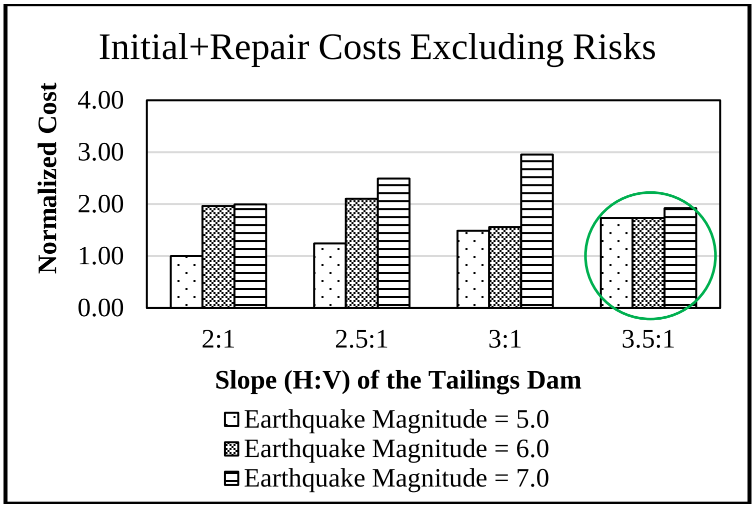

Figure 4: Total cost comparison without consideration of risk

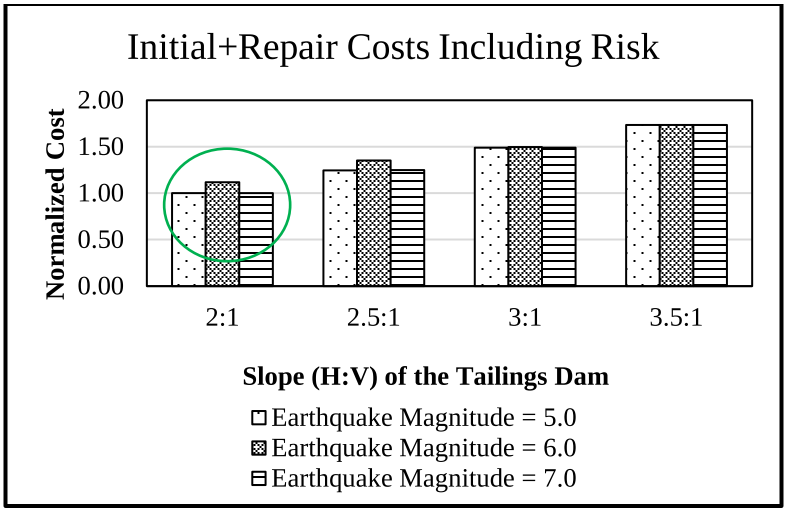

Figure 5: Total cost comparison considering risk

Comparison between the analysis with, and without incorporation of risk shows that the actual cost of the tailings dam may actually be much less than what is shown by only using the discrete methods, and not incorporating risk.

Summary and Conclusion

As proposed in this paper, the framework to assess sustainability, resiliency and risk has been outlined. This framework has the potential to assist decision makers in being able to come up with an effective design that balances the requirements to make the design both sustainable and resilient, by use of analyzing risks of potential hazards. This framework may be utilized for any type of infrastructure, if the proper life cycle costs are known, as well as potential hazards and probabilities of occurrence of those hazards. The example provided in this work showed a basic conceptual method to utilize the framework, but neglected several factors that may be necessary to perform the analysis for actual consideration of alternative designs. Suggested methodologies, along with basic steps of analysis were the goal of this paper, along with providing a simple, yet effective framework that uses risk as a key component into the decision-making process for designing for sustainable and resilient infrastructure. Further work may include developing a systematic process that incorporates all aspects of sustainability and resiliency to obtain a more holistic assessment of a design alternative.

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